

## Sun and Solar–terrestrial Physics

The Sun is of central importance in astronomy. On the one hand, many basic processes that occur throughout the cosmos may be well observed in the Sun and, on the other hand, the Sun acts as a source of the radiation and plasma emissions that affect the Earth in many ways. The study of the interaction of the Sun and its solar wind with the Earth is the burgeoning field of solar–terrestrial physics. The magnetospheres of other planets act as probes for the solar wind. However, many of the fundamental processes, such as how the Sun's magnetic field is generated, how its atmosphere is heated, how solar flares occur and how the solar wind is accelerated, are only just beginning to be understood. This article attempts an overview of the Sun and solar–terrestrial physics and links the individual articles in this encyclopedia into the big picture.

### The Sun

The Sun is of course the nearest star, seen in greatest detail (SUN: BASIC PROPERTIES). The total radiation (SOLAR IRRADIANCE) from the Sun is not constant but, like a variable star, the Sun varies over a variety of timescales. Treated as a star whose properties are more accurately known than most (SUN AS A STAR), the Sun has become a pivotal point in discussion of the abundance of the elements (SOLAR ABUNDANCES) and stellar evolution (SOLAR EVOLUTION). The SOLAR MAGNETIC FIELD plays a key role in many aspects of Solar Physics. It is measured through polarimetry (SOLAR MAGNETIC FIELD: INFERENCE BY POLARIMETRY) and the Zeeman and Hanle Effects (SOLAR MAGNETIC FIELD: ZEEMAN AND HANLE EFFECTS). The solar magnetic field undergoes a cyclic behavior with a period of roughly 22 years (SOLAR CYCLE). Many features of solar activity follow this cycle.

The Sun, indeed most of the Universe, is in the fourth state of matter—the so-called plasma state—in which a gas is so hot that it has become ionized. Its behavior differs from that of a normal gas mainly because it interacts in a complex and subtle way with any magnetic field that is present. Such an interaction is described by the theory of MAGNETOHYDRODYNAMICS, which applies when the ionized particles are much closer than the length-scales of interest, so that the plasma may be regarded as a continuous medium. The magnetic fields are generated within solar and planetary interiors in a self-sustaining way by a process described by DYNAMO THEORY, although the parameter regimes and driving processes are rather different in the GEODYNAMO and in stellar dynamos (DYNAMOS: SOLAR AND STELLAR).

When the force produced on a plasma by a magnetic field dominates all other forces (as is the case, for example, in the upper solar atmosphere), and the magnetic field is in equilibrium with itself, it is said to be a FORCE-FREE MAGNETIC FIELD. Force-free structures can be highly complex and, when they are either twisted or braided around one another, they possess so-called MAGNETIC HELICITY. Equilibrium magnetic fields may be subject to a wide variety of MAGNETOHYDRODYNAMIC INSTABILITIES, which

may produce either a large-scale dynamic behavior or a small-scale structuring of the plasma. In the solar interior, magnetic flux tubes tend to be lighter than their surroundings and so rise by an effect called MAGNETIC BUOYANCY. Also, when heated sufficiently from below, a plasma tends to exhibit turbulent motions due to a convective instability, which, when it interacts with a magnetic field, is known as *magnetoconvection* (see MAGNETOHYDRODYNAMICS: MAGNETOCONVECTION).

In most of the cosmos, magnetic fields are attached or 'frozen' to the plasma and move around with it. The exception is in singular regions where MAGNETIC RECONNECTION can occur and magnetic energy is converted into other forms such as heat, kinetic energy and fast-particle energy. The energy conversion occurs when magnetic field lines are carried into the singularity, broken and rejoined. Several different modes of oscillation (MAGNETOHYDRODYNAMIC WAVES) can be supported in plasmas and are important for transporting energy from one location to another. Several magnetohydrodynamic processes are also crucial in astrophysical circumstances (MAGNETOHYDRODYNAMICS OF ACCRETION DISKS and MAGNETOHYDRODYNAMICS OF ASTROPHYSICAL WINDS).

SOLAR SPECTROSCOPY AND DIAGNOSTICS are invaluable in determining many properties of the plasma such as temperature, density and velocity. The theoretical background lies in atomic physics (SOLAR SPECTROSCOPY: ATOMIC PROCESSES). To access the most complete information about what is happening, astronomers make multiwavelength observations across the whole spectrum (SOLAR SPECTROSCOPY: COHERENT PLASMA EMISSION, SOLAR SPECTROSCOPY: CONTINUUM RADIO EMISSION, SOLAR SPECTROSCOPY: INFRARED EMISSION, SOLAR SPECTROSCOPY: VISIBLE EMISSION, SOLAR SPECTROSCOPY: ULTRAVIOLET AND EXTREME ULTRAVIOLET EMISSION and SOLAR SPECTROSCOPY AND DIAGNOSTICS: X-RAY EMISSION).

Because of the Sun's brightness, its heat and the dynamic range of its phenomena (which may be time-variable), a wide range of special instrumentation has been employed to study the Sun, both from the ground and from space (SOLAR TELESCOPES AND INSTRUMENTS: GROUND and SOLAR TELESCOPES AND INSTRUMENTS: SPACE). Of the space missions, those of particular interest have been the American SKYLAB satellite (1973–1974), the Japanese YOHKO mission (August 1991 to the present), the European Space Agency/NASA SOHO mission (December 1995 to the present), and the American TRACE mission (April 1998 to the present). For analysing data, the SOLARSOFT package is particularly useful.

Of growing interest is the link between activity on the Sun and effects on the Earth's atmosphere—the SOLAR–TERRESTRIAL CONNECTION. A subtle coupling exists between variations in the *solar wind*, the Earth's magnetic environment or *magnetosphere*, the ionized or plasma part of the Earth's atmosphere (the *ionosphere*) and the un-ionized or *neutral atmosphere* (SOLAR–TERRESTRIAL CONNECTION: COUPLING BETWEEN SOLAR WIND, MAGNETOSPHERE, IONOSPHERE AND NEUTRAL ATMOSPHERE). One consequence is that the Earth's

climate is variable, driven by changes in the Sun (SOLAR-TERRESTRIAL CONNECTION: LONG-TERM AND SHORT-TERM CLIMATE VARIABILITY). Satellite observations are being used to predict the effect of the Sun's activity from day to day on the solar wind and the magnetosphere (SOLAR-TERRESTRIAL CONNECTION: SPACE WEATHER PREDICTIONS). Looking outwards from the Sun, there is also enormous interest in what the Sun can tell us about other stars and vice versa (the SOLAR-STELLAR CONNECTION) and in particular about solar-type stars (SOLAR-TERRESTRIAL CONNECTION: ACTIVITY AND BRIGHTNESS CHANGES OF SOLAR-TYPE STARS).

### The solar interior and atmosphere

There are three main regions of the solar atmosphere, namely, the surface layer of the Sun (the SOLAR PHOTOSPHERE), the overlying hotter and rarer CHROMOSPHERE with a temperature of about  $10^4$  K and the much hotter (about  $10^6$  K) and rarer CORONA, which stretches out to the Earth and beyond. The plasma that possesses temperatures between  $10^4$  K and  $10^6$  K comprises the SOLAR TRANSITION REGION.

For the SOLAR INTERIOR a series of standard models has been developed (SOLAR INTERIOR: STANDARD MODELS), based on the best available theories of the properties of the interior material (SOLAR INTERIOR: EQUATION OF STATE AND OPACITY). As a result of the high temperatures and pressures, nuclear energy is released in the solar interior (SOLAR INTERIOR: ENERGY GENERATION) with the release of neutrinos (SOLAR INTERIOR: NEUTRINOS). The plasma in the outer 30% of the solar interior is convectively unstable (SOLAR INTERIOR: CONVECTION ZONE and SOLAR INTERIOR: CONVECTION THEORY). Within the SOLAR INTERIOR: CONVECTION ZONE FLUX TUBES respond to the resulting turbulent motions as well as differential rotation and Coriolis forces. Eventually, from the SOLAR INTERIOR: EMERGING MAGNETIC FLUX TUBES may create sunspots when their flux is large enough.

The Sun rotates (SOLAR INTERIOR: ROTATION). The rotation rate is faster at the equator than the poles and possesses a surprising variation with depth. Gross properties of the SOLAR INTERIOR: SOLAR DIAMETER, OBLATENESS AND TEMPERATURE have dependences on the rotation rate.

Our understanding of the solar interior has been revolutionized by the realization that the Sun is globally oscillating in thousands of modes of vibration (SOLAR INTERIOR: HELIOSEISMIC OBSERVATIONS). Observations have been made both from ground-based networks (BISON NETWORK, GLOBAL OSCILLATION NETWORK GROUP) and the SOHO satellite. The observations lead to properties of the solar interior (SOLAR INTERIOR: HELIOSEISMOLOGY DATA INVERSIONS). HELIOSEISMOLOGY THEORY has been developed in detail, including techniques for inferring properties close to the surface (SOLAR INTERIOR: LOCAL HELIOSEISMOLOGY). MAGNETOHYDRODYNAMICS is used for deducing the influence of magnetic fields (SOLAR INTERIOR: INFLUENCE OF MAGNETIC FIELDS).

For the structure of the atmosphere, empirical models have proved invaluable. Many properties of the SOLAR PHOTOSPHERE change systematically across the face of the Sun (SOLAR PHOTOSPHERE: CENTER-TO-LIMB

VARIATION), and on a smaller scale: *faculae* are small regions that are brighter than normal (SOLAR PHOTOSPHERE: FACULAE) and *filigree* are bright crinkle-shaped ribbons (SOLAR PHOTOSPHERE: FILIGREE). Convection exists on several scales, about 1 Mm (SOLAR PHOTOSPHERE: GRANULATION), a larger scale (SOLAR PHOTOSPHERE: MESOGRANULATION) and an even larger scale of 15 Mm (SOLAR PHOTOSPHERE: SUPERGRANULATION). Over most of the solar surface the magnetic field is far from uniform, being concentrated into intense SOLAR PHOTOSPHERIC MAGNETIC FLUX TUBES at the edges of supergranule cells. In the interior of such cells, the magnetic fields are tangled by convection (SOLAR PHOTOSPHERE: INTRANETWORK AND TURBULENT MAGNETIC FIELDS).

The CHROMOSPHERE is even more non-uniform. A bright *network* surrounds the supergranule cell boundaries (CHROMOSPHERE: NETWORK). Around sunspots the magnetic field is a few hundred gauss and is associated with a brightening of the surrounding region (SOLAR CHROMOSPHERIC PLAGE). Transient brightenings occur near sunspots at the feet of surges (SOLAR CHROMOSPHERE: ELLERMAN BOMBS). Bipolar magnetic flux tubes break through the solar surface (CHROMOSPHERE: EMERGING FLUX REGIONS). Dark *fibrils* due to dense plasma along a *canopy* of magnetic flux tubes cross the interior of supergranule cells (CHROMOSPHERE: FIBRILS and CHROMOSPHERE: CANOPY). Jets of plasma (CHROMOSPHERE: SPICULES) are ejected along flux tubes upwards at the network boundary. SOLAR CHROMOSPHERIC OSCILLATIONS are observed and are related to one of the possible sources of the high temperatures in the chromosphere (CHROMOSPHERE: HEATING MECHANISMS).

The SOLAR TRANSITION REGION is highly dynamic and it is not easy to develop theories (TRANSITION REGION MODELS). There is a variety of flows and small-scale high-velocity features (TRANSITION REGION FLOWS) and TRANSITION REGION: EXPLOSIVE EVENTS. Elemental abundances vary by about a factor of four from place to place. Elements whose neutral atoms have ionization potential larger than about 10 eV are less abundant than those whose neutral atoms are more easily ionized (TRANSITION REGION: FIRST IONIZATION POTENTIAL EFFECT).

The CORONA possesses several different types of structure. CORONAL HOLES have magnetic fields that are open into interplanetary space. POLAR PLUMES are dense rays in coronal holes outlining the magnetic field. CORONAL LOOPS have magnetic field lines that have both ends anchored to the solar surface. Small bright regions (SOLAR CORONA: X-RAY BRIGHT POINTS) occur where magnetic fields are reconnecting. Streams of plasma (SOLAR X-RAY JETS) are accelerated to several hundred  $\text{km s}^{-1}$  by magnetic reconnection. Large-scale structures (CORONAL STREAMERS) are closed below a large fraction of a solar radius above the limb and are open above that height.

The solar corona was traditionally seen only during an ECLIPSE but now can be observed by CORONAGRAPHS from the ground and direct by EUV and x-ray telescopes from space. An important problem is the nature of CORONAL HEATING MECHANISMS. Part of this has been solved, since x-ray bright points are now known to be heated by driven

magnetic reconnection, but it has not yet been established whether coronal loops and coronal holes are heated by magnetic waves of some kind or by magnetic reconnection in many small current sheets.

### Solar activity

The term *solar activity* refers to a wide range of transient solar phenomena that vary in complex ways with the SOLAR CYCLE. SUNSPOTS are dark regions in the photosphere where large thousand-gauss magnetic flux tubes break through the surface. SOLAR ACTIVE REGIONS surround sunspot groups and have fields of a few hundred gauss. SOLAR PROMINENCES are huge flux tubes up in the corona, containing a vertical sheet of plasma at chromospheric temperatures. SOLAR FLARE OBSERVATIONS show how enormous releases of magnetic energy are often related to the eruption of prominences from active regions. SOLAR CORONAL MASS EJECTIONS are large-scale eruptions of mass associated with prominence eruptions, either from active regions or outside active regions.

A variety of SOLAR ACTIVITY INDICES has been proposed for measuring the strength of solar activity. Indeed, solar activity may be traced back many centuries (SOLAR ACTIVITY: LONG-TERM RECORDS). SOLAR ACTIVITY COMPLEXES are active regions that tend to recur in the same location and form. Whereas active regions, like sunspots, occur only in two zones of latitude north and south of the equator, much smaller bipolar regions appear over the whole solar surface at a rate of typically one region per  $27^2 \text{ Mm}^2$  per day (SOLAR ACTIVE REGIONS: EPHEMERAL). Coronal mass ejections produce a wave-like disturbance that propagates ahead of the mass and whose intersection with the solar surface sometimes shows up as MORETON WAVES moving outwards from the site of the eruption.

Prominences are referred to as 'filaments' when observed on the disk, and they form in SOLAR FILAMENT CHANNELS, where the magnetic field is mainly horizontal and directed along a reversal in the sign of the normal component of the field at the solar surface. Quiescent prominences can last for many months but are also of shorter duration (SOLAR PROMINENCES: ACTIVE). Important questions concern SOLAR PROMINENCE FORMATION and SOLAR PROMINENCE FINE STRUCTURE. SOLAR PROMINENCE OSCILLATIONS of various kinds are often observed and their sense of twist exhibits a puzzling global pattern (SOLAR PROMINENCES: CHIRALITY).

SOLAR FLARE CLASSIFICATION has settled to a standard method and much effort has been expended on SOLAR FLARE FORECASTING. The behavior of SOLAR FLARE MAGNETIC FIELDS is crucial to an understanding of SOLAR FLARE MODELS and SOLAR FLARES: PARTICLE ACCELERATION MECHANISMS. The connection between solar flares and coronal mass ejections was for a while a matter of heated debate (SOLAR FLARES: RELATION TO CORONAL MASS EJECTIONS). Solar flares often produce small ejections of mass called *surges* and occasionally give a continuum brightening in the photosphere (SOLAR FLARES: WHITE LIGHT). A solar flare has several phases. Before the flare a prominence starts to rise slowly. The flare rapidly

develops in a few minutes, with a rapid acceleration of *nonthermal electrons*, sometimes producing *gamma rays*. During the *main phase*, the energy release continues for several hours (SOLAR FLARES: PREFLARE PHASE, SOLAR FLARES: IMPULSIVE PHASE, SOLAR FLARES: NONTHERMAL ELECTRONS, SOLAR FLARES: GAMMA RAYS, SOLAR FLARES: MAIN PHASE). In addition, a flare produces different kinds of radio emission (SOLAR FLARES: RADIO BURSTS).

Sunspots often start as small dark patches called SUNSPOT PORES and develop into several different types (SUNSPOT CLASSIFICATION). The central part of the sunspot is dark and is called the *umbra* (SUNSPOT UMBRA: STRUCTURE AND EVOLUTION). The umbra is slightly depressed and so changes its appearance as a sunspot rotates across the solar disk (SUNSPOTS: WILSON EFFECT). The umbra is surrounded by an annulus (the *penumbra*) with radial striations, since the magnetic field is more horizontal (SUNSPOT PENUMBRA: STRUCTURE AND ACTIVITY). The penumbra exhibits a radial outflow (SUNSPOTS: EVERSHED EFFECT). SUNSPOT OSCILLATIONS AND SEISMOLOGY are used to infer the structures of sunspots and SUNSPOT MODELS for the structures have been developed in detail. SUNSPOT MAGNETIC FIELDS tend to be vertical at the centers of sunspots and then to become more horizontal as one moves outwards from the axis, as the vertical flux tube spreads out through the photosphere. SUNSPOT EVOLUTION follows a standard pattern. A radial *moat flow* of plasma away from a sunspot carries magnetic flux outwards (SUNSPOTS: MOVING MAGNETIC FEATURES AND MOAT FLOW).

### The solar heliosphere

The *solar wind* is the outwards expansion of the corona from the Sun. It is described in a general article (SOLAR WIND: GLOBAL PROPERTIES). SOLAR WIND: THEORY describes its structure and SOLAR WIND ACCELERATION how it gains in velocity. The SOLAR WIND COMPOSITION and SOLAR WIND KINETIC PROPERTIES are highly complex. Both *waves* and *turbulence* and *shock waves* make up its structure (SOLAR WIND PLASMA WAVES, SOLAR WIND TURBULENCE, SOLAR WIND SHOCK WAVES AND DISCONTINUITIES) and the SOLAR WIND: MAGNETIC FIELD is highly variable. Especially interesting is the behavior out of the ecliptic plane as measured by the only satellite to orbit in that region (SOLAR WIND: ULYSSES).

Neighboring streams that are flowing out from the Sun interact at their boundaries (SOLAR WIND: COROTATING INTERACTION REGIONS). Accelerated particles (SOLAR WIND: ENERGETIC PARTICLES) of many types are observed; they produce bursts of radio waves (SOLAR WIND: INTERPLANETARY RADIO BURSTS) which are a valuable diagnostic (SOLAR WIND: RADIO TECHNIQUES FOR PROBING). COSMIC RAYS may give rise to showers of electrons and other particles when they impact on the Earth's atmosphere (COSMIC RAYS: EXTENSIVE AIR SHOWERS). Their propagation has been modeled in detail (COSMIC RAYS: PROPAGATION IN THE HELIOSPHERE). Those with energies up to 100 MeV and which lie between the energies of normal heliospheric particles and galactic cosmic rays are known as ANOMALOUS COSMIC RAYS.

The solar wind is rooted in the corona (SOLAR WIND: CORONAL ORIGINS) and is sensitive to solar activity (SOLAR

WIND: MANIFESTATIONS OF SOLAR ACTIVITY). Venus interacts with the solar wind as it flows through the heliosphere (VENUS: INTERACTION WITH THE SOLAR WIND), as do other planets and also COMETS (SOLAR WIND: INTERACTION WITH COMETS). Kreutz discovered a family of comets that approach close to the Sun (COMETS: KREUTZ SUNGRAZERS), many of which have been discovered by the LASCO instrument on the SOHO satellite. At the heliopause, the solar wind connects with the rest of the Galaxy (SOLAR WIND: INTERACTION WITH LOCAL INTERSTELLAR MEDIUM).

PLANETARY MAGNETOSPHERES are the magnetized plasma environments of the planets. A range of planets have been studied, including JUPITER: MAGNETOSPHERE and SATURN: MAGNETOSPHERE, as well as MERCURY: MAGNETOSPHERE, URANUS AND NEPTUNE: ATMOSPHERES, IONOSPHERES AND MAGNETOSPHERES. Planetary satellites are of particular interest (SATURN: MAGNETOSPHERE INTERACTION WITH TITAN, MAGNETOSPHERES: JUPITER, SATELLITE INTERACTIONS, MAGNETOSPHERES: JUPITER, RADIO EMISSION, IO: PLASMA TORUS).

### The Earth's magnetosphere

Due to its proximity to us, the MAGNETOSPHERE OF EARTH has been extensively studied in great detail and presents an opportunity to understand the behavior of many basic plasma processes. Since the magnetosphere acts as an obstacle to the supermagnetosonic solar wind, a *bow shock* stands in the flow ahead of the Earth (MAGNETOSPHERE OF EARTH: BOW SHOCK). The surface that separates the Earth's magnetic field from the solar wind magnetic field is called the *magnetopause* (MAGNETOSPHERE OF EARTH: MAGNETOPAUSE). Between the bow shock and the magnetopause lies the *magnetosheath*. The Earth's magnetic field is swept downstream by the solar wind to form a long tail (MAGNETOSPHERE OF EARTH: GEOMAGNETIC TAIL), the central and densest part of which is called the *plasma sheet* (MAGNETOSPHERE OF EARTH: PLASMA SHEET). Between the magnetic field that closes on the dayside of the Earth and the tail field that is swept down on the nightside lies the *dayside cusp* (MAGNETOSPHERE OF EARTH: DAYSIDE CUSP).

Within the closed part of the Earth's magnetic field there lie: a *ring current* (MAGNETOSPHERE OF EARTH: RING CURRENT) which flows westward roughly in a circle in the equatorial plane about the Earth; the *radiation belts*, consisting of trapped particles in orbits that circle the Earth from about 1000 km above the surface to about six Earth radii (MAGNETOSPHERE OF EARTH: RADIATION BELTS); a population of cold dense plasma (*plasmasphere*) that coexists with the radiation belts (MAGNETOSPHERE OF EARTH: PLASMASPHERE). Streams of energetic particles impacting the Earth's upper atmosphere in a ring around each of the Earth's poles form the *aurorae* and excite AURORAL KILOMETRIC RADIATION. Within the magnetosphere there is a wide range of waves (MAGNETOSPHERE OF EARTH: WAVES). Also, the rotation of the Earth and the flow of the solar wind cause the plasma and magnetic field lines within the magnetosphere to move in a complex pattern (MAGNETOSPHERE OF EARTH: CONVECTION). Regions of enhanced solar wind flow compress the magnetosphere

(MAGNETOSPHERE OF EARTH: GEOMAGNETIC STORMS AND SOLAR WIND ORIGINS) for 1–5 days. *Substorms* occur for 1–3 hours in response to a sustained southward turning of the interplanetary magnetic field, after which the tail of the magnetosphere goes unstable and reconnects (MAGNETOSPHERE OF EARTH: SUBSTORMS). This causes a plasmoid to be formed in the tail and ejected downstream and accelerates fast particles that greatly enhance the aurorae.

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